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13. SUPPLEMENTARY NOTES

14. ABSTRACT

This project concerned integrated laboratory and analytical modeling of internal tide generation by sea floor topography. A Green function approach was developed to handle arbitrary two-dimensional topography in arbitrary stratifications, and the method was validated through comparison with numerical models and laboratory experiments. The resulting method was encoded as a MATLAB toolbox called iTides. Large scale laboratory experiments were performed at the Coriolis facility in Grenoble, France and the resulting data confirmed the nature of the internal wave generation process in the South China Sea to be the steeping of a weakly-nonlinear, low-mode internal tide. Advances in laboratory experimental techniques for generating and studying internal waves were made, including the first 3D stereoscopic PIV studies of an internal wave field and the development of a novel internal wave generator. A major overview manuscript for the IWISE program was prepared and is in review, and there are nine other publications. The PI and members of his group participated in the 2010 and 2011 field programs.

15. SUBJECT TERMS

Internal Waves, Laboratory Experiments, Internal Wave Attractors, Green Function Analysis, iTides

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Laboratory Modeling of Internal Wave Generation in Straits
Final Report

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LONG-TERM GOALS

The primary long term goal of this project was to combine theoretical modeling and laboratory experimentation in support of the efforts of field studies and numerical simulations to study and understand internal wave generation in the South China Sea, and more generally support internal wave modeling capabilities elsewhere in the oceans.

OBJECTIVES

The specific objectives were to address the uncertainty regarding the nature of generation mechanism, which has been a souce of substantial ambiguity. In addition, we sought to produce a validated semi-analytical tool for investigating internal tide generation that could be widely utilized by our collegaues.

APPROACH

In regards to the laboratory experiments, we used a combination of smaller scale laboratory experiments in our ENDLab facility at MIT and large scale experiments at the Coriolis facility in Grenoble, France, the latter with the assistance of an assebled international team of researchers. A summary of the experimental arrangement at the Coriolis facility is presented in Figure 1 and its associated caption, and a summary of the dimensional and nondimensional operating parameters are presented in Tables 1 and 2, respectively. For the analytical studies, we advanced the Green Function method of solving internal tide genartion problems to address arbitrary two-dimensional topographic feautres in arbitrary stratifications, ultimately removing the need to use the WKB approximation that is known to be most ineffective for the energetically important low mode internal wave field. Novel internal wave generation technology was developed and utilized to study internal wave propagation in arbitrary density stratifications.

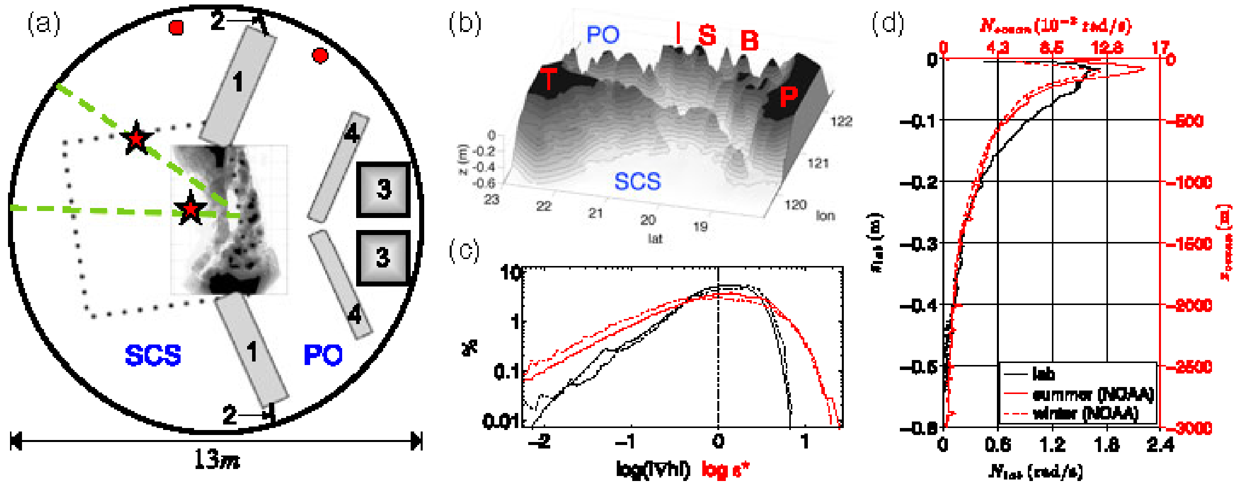

Figure 1. (a) Schematic of the Coriolis experiment. Vertical partitions (1) extend from Taiwan and The Philippines to the side of the tank. After filling, the PO and SCS are separated using inserted barriers (2) and the barotropic tide is generated using prismatic plungers (3) located behind vertical walls (4). Dashed green lines and the dotted square indicate the vertical PIV planes and overhead field of view, respectively. Red stars and circles indicate the location of the CT and acoustic probes, respectively. (b) The experimental topography, with Taiwan (T), the Philippines (P), Itbayat Island (I), Sabtang and Batan Islands (S), and Babuyan Island (B) indicated. (c) Distributions of the topographic slope (black) and the criticality parameter ε (red) for the experiments (solid) and the ocean (dashed). The ocean slopes have been multiplied by 20 to match the laboratory range. (d) Typical winter and summer stratifications (red) in the LS, compared to a laboratory stratification (black).*

Table 1. Characteristic Values of Key Dimensional Parameters for Internal Tide Generation on the Scale of the Luzon Strait (*Luzon*) and on the Local Scale (*Batanes*)[a]

	ω (rad/s)	f (rad/s)	N_m (rad/s)	N_b (rad/s)	U_0 (m/s)	δ (m)	H (m)	L (m)	h_0 (m)	ν (m^2/s)
Luzon	1.40×10^{-4}	5.00×10^{-5}	1.57×10^{-2}	3.65×10^{-4}	0.1	100	3.0×10^{3}	10^{5}	1.5×10^{3}	10^{-4}
Batanes	1.40×10^{-4}	5.00×10^{-5}	1.57×10^{-2}	1.28×10^{-3}	1.0	100	1.5×10^{3}	10^{4}	8.0×10^{2}	10^{-4}
Lab_L	3.86×10^{-1}	1.38×10^{-1}	2.21	5.15×10^{-2}	2.76×10^{-3}	0.02	0.6	1.0	0.30	10^{-6}
Lab_B	3.86×10^{-1}	1.38×10^{-1}	2.21	1.80×10^{-1}	2.76×10^{-2}	0.02	0.3	0.1	0.16	10^{-6}
$\frac{Lab_L}{Luzon}$	2.76×10^{3}	2.76×10^{3}	1.41×10^{2}	1.41×10^{2}	2.76×10^{-2}	2×10^{-4}	2×10^{-4}	10^{-5}	5×10^{3}	10^{2}

[a]The corresponding laboratory values are Lab_L and Lab_B, respectively. The scaling factor relating laboratory values to the ocean ones is indicated at the last line.

Table 2. Characteristic Values of Key Dimensionless Parameters for the Ocean and the Measured Experimental Values[a]

	h^*	δ^*	h_0/L	N^*	ε^*	Re^*	Ro^*	A^*	Lo^*	Fr_1^*	Fr_2^*
Luzon	0.50	3.3×10^{-2}	1.5×10^{-2}	43.0	[0.004 – 14]	1.0×10^{8}	2.0×10^{-2}	7.14×10^{-3}	2.5×10^{-2}	3.6×10^{-2}	7.3×10^{-2}
Batan	0.53	6.6×10^{-2}	8.0×10^{-2}	12.3	[0.004 – 14]	1.0×10^{8}	2.0	7.14×10^{-1}	2.7×10^{-1}	4.2×10^{-1}	8.3×10^{-1}
Lab_L	0.50	2.7×10^{-2}	0.3	42.0	[0.01 – 14]	2.76×10^{3}	2.0×10^{-2}	7.15×10^{-3}	1.2×10^{-2}	2.1×10^{-2}	4.3×10^{-2}
Lab_B	0.53	5.5×10^{-2}	1.6	1.82	[0.01 – 14]	2.76×10^{3}	2.0	7.15×10^{-1}	3.5×10^{-1}	8.9×10^{-1}	1.8
$\frac{Lab_L}{Luzon}$	1.0	0.82	20	0.98	0(1)	2.76×10^{-5}	1.0	1.00	0.5	0.6	0.6

[a]The ratio of laboratory to ocean values actually achieved is given at the end of the table.

WORK COMPLETED

The laboratory experimental program and the analytical modeling have all been completed within the time line of the project. Overall, this has lead to 10 publications, numerous conference presentations and invited talks, and the production of a software tool *iTides*. A major publication on the outcomes of the IWISE project has been prepared by ourselves and Matthew Alford, and is currently in review at Nature (Alford, Peacock *et al.* 2014). Members of the ENDLab team participated in the field programs in 2010 and 2011. Two postdocs and three graduate students were trained via this funding.

RESULTS

1. The primary result is the determination by the large-scale experiments at the Coriolis platform that the generation mechanism of large amplitude solitary internal waves in the South China Sea is the steepening of the weakly-nonlinear, low-mode internal tide. Details of these results are presented in Figure 2 and associated caption, and summarized in Mercier *et al.* (2013).

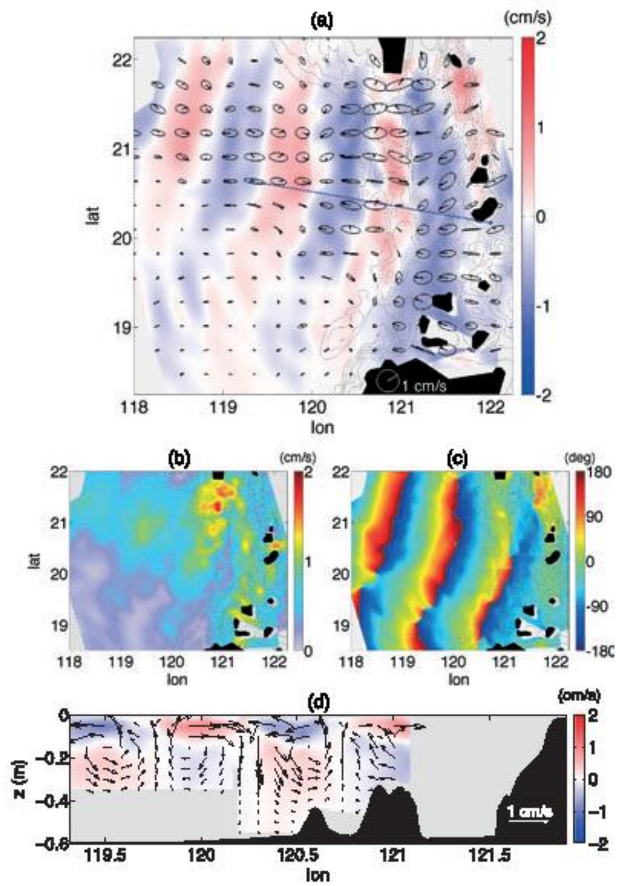

Figure 2: (a) Colormap of the east-west velocity in the isopycnal plane at z = –0.04 m at an instant of barotropic tide flow reversal. The black arrows inside the tidal ellipses indicate the local velocity direction. (b) Amplitude of the total velocity and (c) phase of the east-west velocity of the combined M2 baroclinic and barotropic tides, filtered at the forcing frequency. (d) Data are the same as those in Figure 2a for the vertical transect indicated by the dashed blue line in Figure 2a; arrows indicate the in-plane velocity field.

2. We advanced the Green function method significantly to handle internal tide generation for reaslistic topographic features and realistic stratifications using the WKB approximation (Echeverri & Peacock 2010), and more recently without the need for the WKB approximation (Mathur, Carter & Peacock 2014). As an example, Figure 3 presents the internal wave field for a cross section of the Luzon Strait calculated using the WKB Green function approach.

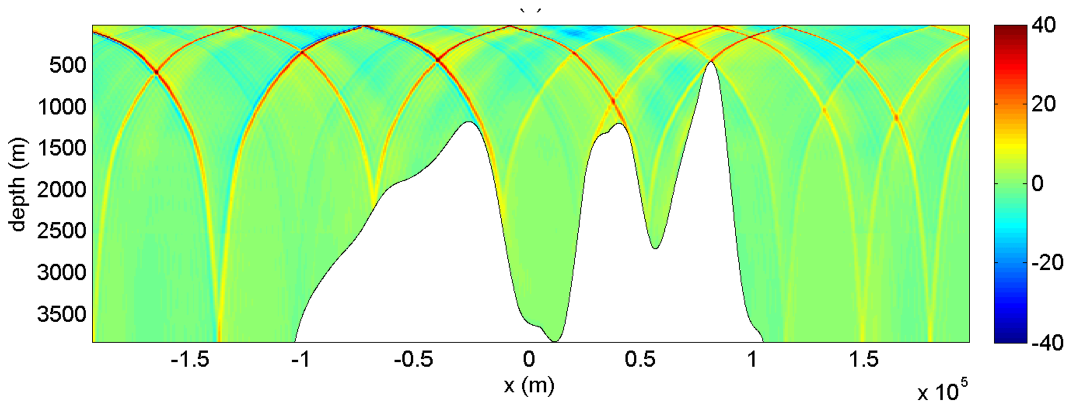

Figure 3: Normalized horizontal velocity field assocaited with barotropic tidal flow over a cross section of the Luzon Strait, calculated using the Green Function approach (Echeverri & Peacock 2010).

3. The suitability of the double ridge configuration of the Luzon Strait to give rise to resonant forcing of the semi-diurnal internal tide, and the potential existence of internal wave attractors, was revealed (Tang & Peacock 2010; Echeverri *et al.* 2011). Figure 4 illustrates the existence of an internal wave attractor for a double ridge system.

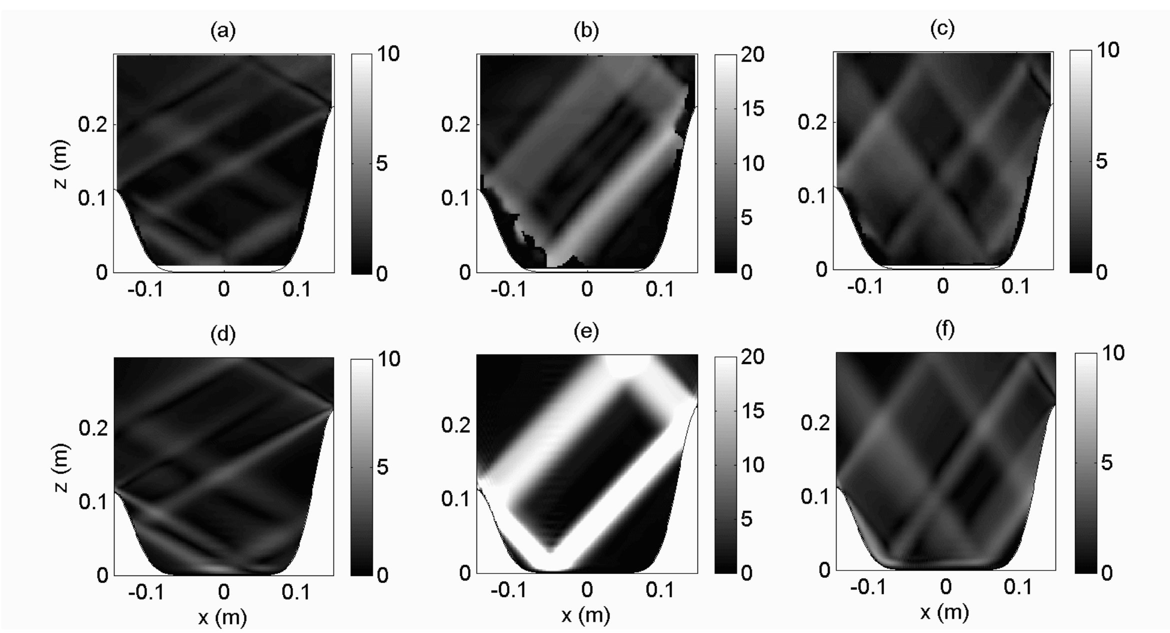

Figure 4: (top row) Model prediction of internal wave field for three different forcing frequencies. (bottom row) Corresponding experimental wave fields, confirming the existsnce of an internal wave attractor for an intermediate forcing frequency (Echeverri et al. 2011).

4. The propagation of internal wave beams through arbitrary stratifications was analyzed and a novel analytical method for handling this scenario was developed. The ability of the ocean stratification to selectively filter internal waves based on their wavelength and frequency was identified and demonstrated experimentally (Mathur & Peacock 2009, 2010). Figure 5 presents an example result.

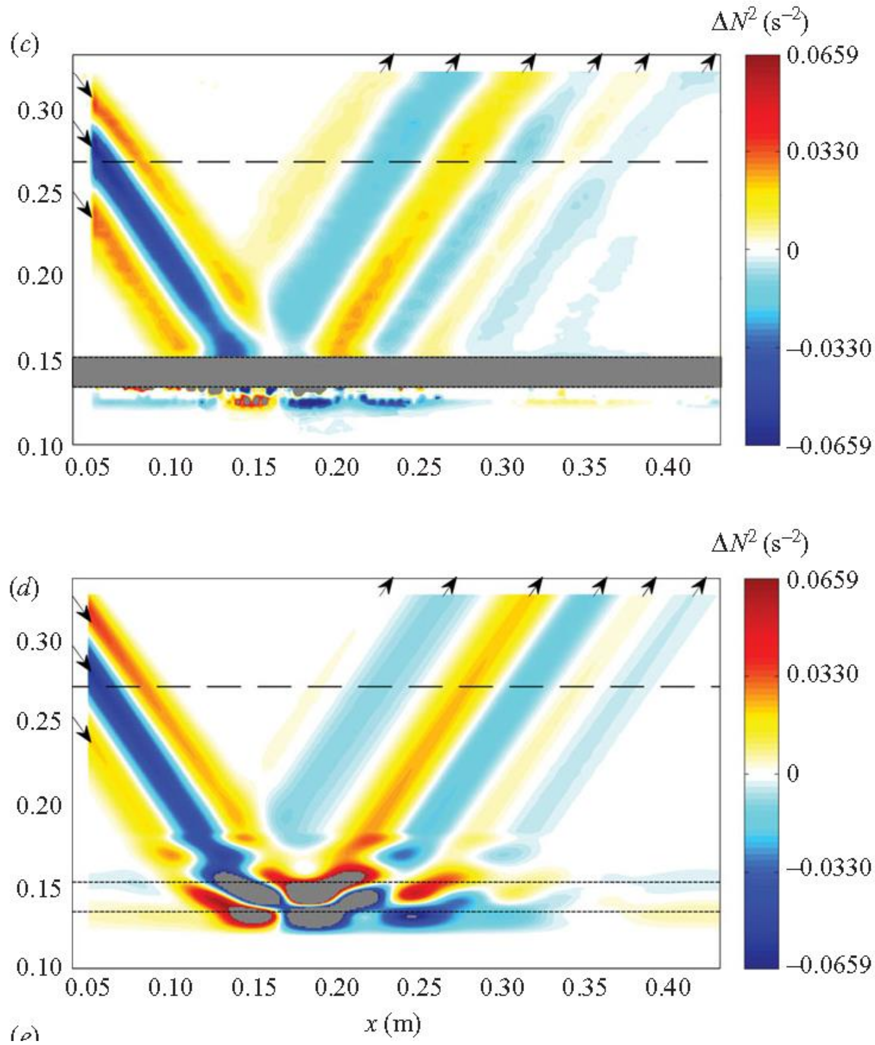

Figure 5: (top) Laboratory experimental study of an intern wave beam being reflected from a sharp pycnocline. (bottom) Corresponding theoretical prediction based using the novel analytical approach.

5. We performed the first laboratory investigations of a three-dimensional internal wave field using stereoscopic PIV and demonstrated the accuracy of the method by comparison with the predictions of an analytical model (Ghaemsaidi & Peacock 2013). These results pave the way for future studies of three-dimensional internal wave fields. A sample set of results is presented in Figure 6.

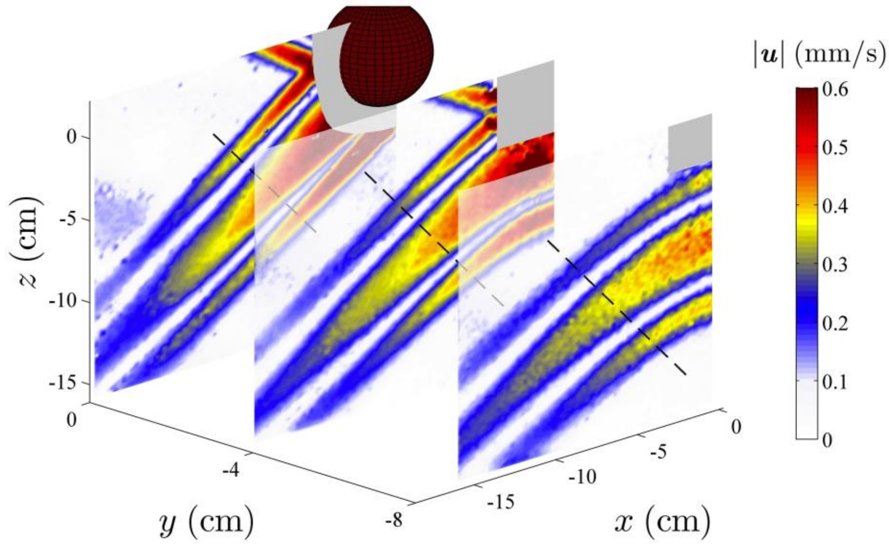

Figure 6: PIV visualization of the magnitude of the in-plane velocity of the 3D conical internal wave field generated by a vertically oscillating sphere.

TRANSITIONS

The software *iTides* is hosted on the PIs website (http://web.mit.edu/endlab) and is being used by several members of the IWISE to calcuate internal tide generation. A screenshot of the *iTides* host page is shown in figure 7, below.

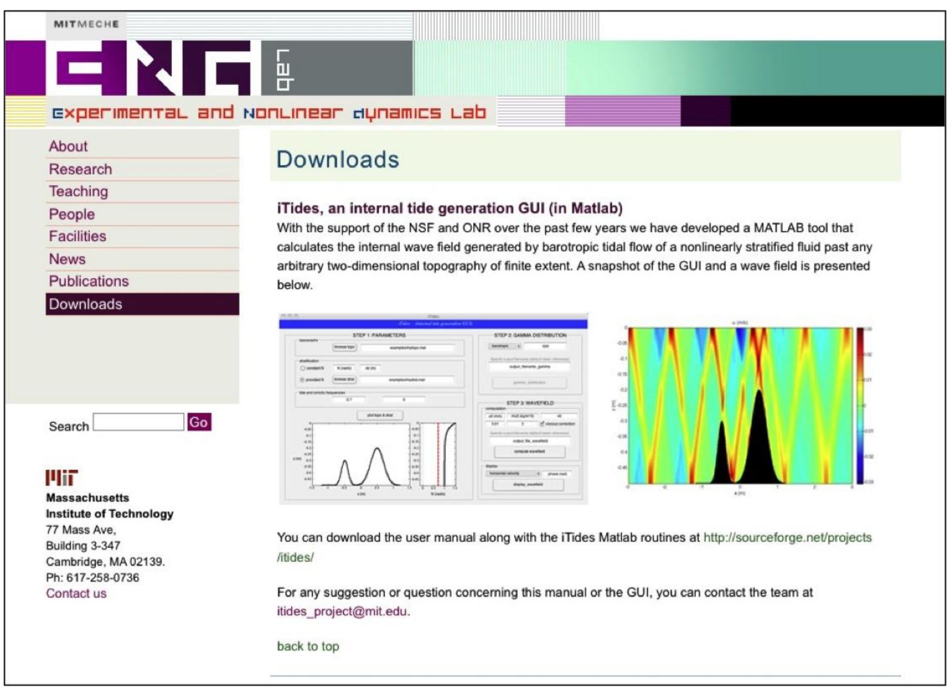

Figure 7: A screen shot of the iTides website.

RELATED PROJECTS

None

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None

PUBLICATIONS

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